

INVESTIGATION OF AIR FLOW
NEAR A MACH NUMBER OF ONE,
BY THE SCHLIEREN METHOD

BY
DAVID WAYNE WATKINS, JR.

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Cambridge, Massachusetts,
June 3, 1946.

Professor George W. Swett,
Secretary of the Faculty,
Massachusetts Institute of Technology,
77 Massachusetts Avenue,
Cambridge, Massachusetts.

Dear Professor Swett:

Herewith I submit my thesis entitled, "Investigation
of Air Flow Near a Mach Number of One, by the Schlieren
Method" in partial fulfillment of the requirements for the
degree of Master of Science in Aeronautical Engineering at
the Massachusetts Institute of Technology.

Respectfully,

David W. Watkins, Jr.
David W. Watkins, Jr.

Cambridge, Massachusetts,
June 3, 1944.

Professor George A. Davis,
Secretary of the Faculty,
Massachusetts Institute of Technology,
75 Massachusetts Avenue,
Cambridge, Massachusetts.

Dear Professor Davis:

Herewith I submit a copy of a letter dated
of air flow over a semi-circular airfoil, by the author
written in partial fulfillment of the requirements for the
degree of Master of Science in Aeronautical Engineering at
the Massachusetts Institute of Technology.

Very truly,
David W. Johnston

David W. Johnston
David W. Johnston, Jr.

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INVESTIGATION OF AIR FLOW NEAR A MACH NUMBER OF ONE,
BY THE SCHLIEREN METHOD

by

David Wayne Watkins, Jr.
Lt. Comdr., U. S. Navy.

Submitted in Partial Fulfillment of the
Requirements for the
Degree of Master of Science
in
Aeronautical Engineering
from the
Massachusetts Institute of Technology
1946

Signature of Author:

David W. Watkins, Jr.

Department of Aeronautical Engineering, June 1946.

Signature of Professor in Charge of
Research:

Joseph H. Keenan

Signature of Chairman of Department
Committee on Graduate Students:

C. S. Draper

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Department of Agricultural Research, June 1940.

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Signature of subject:
Department of Agricultural Research, June 1940.
Signature of Professor in Charge of
Department
Signature of Director of Department
Signature of Professor in Charge of

ACKNOWLEDGMENTS.

It is with pleasure that I acknowledge my indebtedness to Professor J. H. Keenan, who suggested the thesis problem and the possible lines of attack, and helped me constantly through conference on the many difficulties I encountered. Mr. E. P. Neumann also gave freely of his time and offered many valuable suggestions, especially in connection with the investigation of the boundary layer. Mr. A. H. Shapiro suggested an explanation of the multiple shocks observed. Mr. F. Lustwerk explained the use of the Schlieren equipment, and helped with collateral reading. Professor H. E. Edgerton lent his high speed movie equipment, explained its use, and aided me in the development of the film. Mr. Charles Wyckoff gave many days of his time operating the movie equipment. The personnel of the Boston Naval Shipyard permitted free use of their photographic laboratory and helped me with printing the pictures.

INTERVIEW

It is also possible that I am overlooking an investigation
by Professor J. H. Brown, who suggested the film problem
and the possible lines of attack, and helped me considerably
throughout the work on the very difficult problem I encountered.
Mr. J. H. Brown also gave credit to his film and offered
many valuable suggestions, especially in connection with the
investigation of the possible impact. Mr. J. H. Brown was
granted an explanation of the entire process of the film.
J. H. Brown explained the use of the film in the
and helped with various details. Professor J. H. Brown
and his film used movie equipment, explained the use, and
also as it is the development of the film. Mr. Brown spent
great many days of his time operating the movie equipment.
The personnel of the Brown Hotel College provided free use
of their photographic laboratory and helped me with printing
the pictures.

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SUMMARY.

The problem investigated was the manner of dissipation of shocks in air flowing through a nozzle. The shocks observed were oblique shocks. They were formed by decreasing the back pressure on the nozzle exit by means of an ejector. The mouth of the nozzle was open to laboratory air. The back pressure was increased after the shocks were formed by closing the valve between the nozzle exit and the ejector, causing dissipation of the shocks. The phenomena were observed by means of a high speed movie camera. The results indicated that the shocks formed dissipated in the throat of the nozzle. They were never observed upstream from the throat.

INTRODUCTION.

In a Schlieren study of two dimensional ejectors, Mr. F. Lustwerk noted the appearance of a sharp fronted disturbance in the subsonic secondary stream under certain conditions. It was desired to know how long the secondary stream could support this disturbance and the manner of its dissipation.

It was decided to simplify the problem by removing the primary stream from the ejector; that is, to investigate the dissipation of a shock in a two dimensional nozzle. This was done to reduce the number of variables involved, so that some results could be obtained in the allotted time.

To attack this problem, it was decided to set up a convergent-divergent nozzle which was supplied by opening the mouth of the nozzle to the atmosphere, to keep entering turbulence as low as possible, and to supply the necessary controlled pressure drop by means of an ejector and suitable valves. Then the phenomena related to the dissipation of the shocks formed in the nozzle could be observed through a Schlieren optical system and recorded on a photographic medium. A few single flash pictures were taken to ascertain that there were dynamic effects to be observed. Then high speed movies were taken of these effects.

It is interesting to note that the same type of error is also found in the work of the same author in the same year, 1934, in the paper on the "Theory of the Structure of the Atom".

It was decided to study the problem of removing the primary stream from the system; that is, to investigate the elimination of a shock in a two-dimensional system. This was done to reduce the number of variables involved, as this same variable occurs in the adjacent case. To attack this problem, it was decided to set up a two-dimensional system which was simplified by opening the front of the shock in the atmosphere, to keep entering air at a low pressure, and to supply the necessary controlled pressure from a source of an ejector and maintain it. Then the phenomenon related to the elimination of the shock formed in the shock field is observed through a controlled optical system and recorded on a photographic system. A few studies have shown that the shock waves were formed at a distance of 100 mm. This distance was taken at 100 mm.

APPARATUS.

The major piece of equipment used in this investigation was a double pass Schlieren optical system. Fig. 1 is a sketch of this apparatus, and a more complete description and discussion of it is given in the Appendix.

The nozzle used was a convergent-divergent two dimensional nozzle made of mild steel, with glass end walls. The nozzle was one-half inch wide and for a distance of one-half inch was parallel to the longitudinal axis of the nozzle. The entry to the throat consisted of the arcs of two circles of six inch radii, and extended about three and one-half inches along the longitudinal axis. (See Fig. 2.) The divergent portion of the nozzle consisted of two planes placed at a four degree slope away from the longitudinal axis. The corner between the throat section and the divergent section was carefully blended to destroy the sharp corner. Fig. 3 is a drawing of the frame used to mount the test section. Fig. 4 is a sketch of the nozzle assembly as it was used. The glass walls of the nozzle were made of high grade optical glass, and the surfaces were ground optically flat and parallel.

To take the pictures shown in the results, a standard "Edgerton type", high speed, thirty-five millimeter movie camera was used with an air gap spark substituted for the Edgerton flash tube as a light source. The Appendix fully describes this apparatus and Fig. 5 is a schematic wiring diagram of the light source.

APPENDIX

The major part of the investigation was in this investigation
was a large scale examination of the system of this apparatus, and a more complete description
and discussion of it is given in the Appendix.
The results show that a convenient-divided two sided-
electrical system made of mild steel, with glass and water. The
results are one-half inch wide and for a distance of one-half
inch are parallel to the longitudinal axis of the nozzle.
The only in the largest diameter of the area of two circles
of six inch width, and extending about three and one-half
inches along the longitudinal axis. (See Fig. 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115, 116, 117, 118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128, 129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140, 141, 142, 143, 144, 145, 146, 147, 148, 149, 150, 151, 152, 153, 154, 155, 156, 157, 158, 159, 160, 161, 162, 163, 164, 165, 166, 167, 168, 169, 170, 171, 172, 173, 174, 175, 176, 177, 178, 179, 180, 181, 182, 183, 184, 185, 186, 187, 188, 189, 190, 191, 192, 193, 194, 195, 196, 197, 198, 199, 200, 201, 202, 203, 204, 205, 206, 207, 208, 209, 210, 211, 212, 213, 214, 215, 216, 217, 218, 219, 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2178, 2179, 2180, 2181, 2182, 2183, 2184, 2185, 2186, 2187, 2188, 2189, 2190, 2191, 2192, 2193, 2194, 2195, 2196, 2197, 2198, 2199, 2200, 2201, 2202, 2203, 2204, 2205, 2206, 2207, 2208, 2209, 2210, 2211, 2212, 2213, 2214,

The film used was Eastman Kodak Company's "Super XI", developed for maximum contrast in the same Company's standard developer "D-11" for sixteen minutes. For further discussion of the photography methods see the Appendix.

The required pressure difference across the nozzle was obtained by reducing the downstream pressure from atmosphere by means of an ejector.

The flow of air was from atmosphere, through the test section, suitable piping, a butterfly valve, a silencer, and a globe valve to the secondary stream of the ejector.

In taking a high speed series of pictures, the following procedure was used. The pressure difference across the nozzle was adjusted by use of the globe valve, until a shock was observed in the aperture of the camera. The general illumination in the laboratory was switched off, and the camera was started. The butterfly valve, which was spring loaded to the wide open position, was manually closed. Next, it was allowed to open fully. This valve cycle was repeated two or three times during the exposure of a hundred feet of film. The film speed through the camera averaged about fifty feet per second. This made the time interval between exposures about one five-hundredth of a second. The exposure time of each exposure was about five microseconds.

The film used was Kodak's "Super 8",

developed for sixteen minutes in Kodak D-19.

One exposure "8-11" for sixteen minutes. For further

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RESULTS.

The results are presented as pictures in Figs. 6 through 32. They are selected series of enlargements made from one of the hundred foot lengths of exposures made in the high speed camera. The whole length contains about twelve hundred exposures, many of which would be of no interest. In selecting the pictures to be presented, an attempt was made to select those demonstrating most clearly the phenomena occurring in the fewest number of exposures. Since time was an element of interest in the investigation, the continuity of each series was maintained; that is, within each series, the pictures presented follow each other in sequence, with a time interval between pictures of one five-hundredth of a second. The boundary layer group of pictures are an exception to this in that they were of necessity made on another strip of film and were isolated selections and not a continuous series.

Figs. 6 through 13 are one series. This series demonstrates the nature of the multiple shocks at a pressure ratio somewhat below critical, and are from a section of the film in which no change was occurring in the back pressure. They show clearly the oscillations of the shocks occurring in the "steady state" condition.

Figs. 14 through 18 show the manner of dissipation of the shocks with increasing pressure ratio.

Figs. 19 through 27 show the manner of formation of the shock with decreasing pressure ratio.

RESULTS

The results are presented in Figures 1 through 5. Figure 1 shows the results of the first series of experiments. The results of the second series are shown in Figure 2. The results of the third series are shown in Figure 3. The results of the fourth series are shown in Figure 4. The results of the fifth series are shown in Figure 5. The results of the sixth series are shown in Figure 6. The results of the seventh series are shown in Figure 7. The results of the eighth series are shown in Figure 8. The results of the ninth series are shown in Figure 9. The results of the tenth series are shown in Figure 10. The results of the eleventh series are shown in Figure 11. The results of the twelfth series are shown in Figure 12. The results of the thirteenth series are shown in Figure 13. The results of the fourteenth series are shown in Figure 14. The results of the fifteenth series are shown in Figure 15. The results of the sixteenth series are shown in Figure 16. The results of the seventeenth series are shown in Figure 17. The results of the eighteenth series are shown in Figure 18. The results of the nineteenth series are shown in Figure 19. The results of the twentieth series are shown in Figure 20. The results of the twenty-first series are shown in Figure 21. The results of the twenty-second series are shown in Figure 22. The results of the twenty-third series are shown in Figure 23. The results of the twenty-fourth series are shown in Figure 24. The results of the twenty-fifth series are shown in Figure 25. The results of the twenty-sixth series are shown in Figure 26. The results of the twenty-seventh series are shown in Figure 27. The results of the twenty-eighth series are shown in Figure 28. The results of the twenty-ninth series are shown in Figure 29. The results of the thirtieth series are shown in Figure 30. The results of the thirty-first series are shown in Figure 31. The results of the thirty-second series are shown in Figure 32. The results of the thirty-third series are shown in Figure 33. The results of the thirty-fourth series are shown in Figure 34. The results of the thirty-fifth series are shown in Figure 35. The results of the thirty-sixth series are shown in Figure 36. The results of the thirty-seventh series are shown in Figure 37. The results of the thirty-eighth series are shown in Figure 38. The results of the thirty-ninth series are shown in Figure 39. The results of the fortieth series are shown in Figure 40. The results of the forty-first series are shown in Figure 41. The results of the forty-second series are shown in Figure 42. The results of the forty-third series are shown in Figure 43. The results of the forty-fourth series are shown in Figure 44. The results of the forty-fifth series are shown in Figure 45. The results of the forty-sixth series are shown in Figure 46. The results of the forty-seventh series are shown in Figure 47. The results of the forty-eighth series are shown in Figure 48. The results of the forty-ninth series are shown in Figure 49. The results of the fiftieth series are shown in Figure 50. The results of the fifty-first series are shown in Figure 51. The results of the fifty-second series are shown in Figure 52. The results of the fifty-third series are shown in Figure 53. The results of the fifty-fourth series are shown in Figure 54. The results of the fifty-fifth series are shown in Figure 55. The results of the fifty-sixth series are shown in Figure 56. The results of the fifty-seventh series are shown in Figure 57. The results of the fifty-eighth series are shown in Figure 58. The results of the fifty-ninth series are shown in Figure 59. The results of the sixtieth series are shown in Figure 60. The results of the sixty-first series are shown in Figure 61. The results of the sixty-second series are shown in Figure 62. The results of the sixty-third series are shown in Figure 63. The results of the sixty-fourth series are shown in Figure 64. The results of the sixty-fifth series are shown in Figure 65. The results of the sixty-sixth series are shown in Figure 66. The results of the sixty-seventh series are shown in Figure 67. The results of the sixty-eighth series are shown in Figure 68. The results of the sixty-ninth series are shown in Figure 69. The results of the seventieth series are shown in Figure 70. The results of the seventy-first series are shown in Figure 71. The results of the seventy-second series are shown in Figure 72. The results of the seventy-third series are shown in Figure 73. The results of the seventy-fourth series are shown in Figure 74. The results of the seventy-fifth series are shown in Figure 75. The results of the seventy-sixth series are shown in Figure 76. The results of the seventy-seventh series are shown in Figure 77. The results of the seventy-eighth series are shown in Figure 78. The results of the seventy-ninth series are shown in Figure 79. The results of the eightieth series are shown in Figure 80. The results of the eighty-first series are shown in Figure 81. The results of the eighty-second series are shown in Figure 82. The results of the eighty-third series are shown in Figure 83. The results of the eighty-fourth series are shown in Figure 84. The results of the eighty-fifth series are shown in Figure 85. The results of the eighty-sixth series are shown in Figure 86. The results of the eighty-seventh series are shown in Figure 87. The results of the eighty-eighth series are shown in Figure 88. The results of the eighty-ninth series are shown in Figure 89. The results of the ninetieth series are shown in Figure 90. The results of the ninety-first series are shown in Figure 91. The results of the ninety-second series are shown in Figure 92. The results of the ninety-third series are shown in Figure 93. The results of the ninety-fourth series are shown in Figure 94. The results of the ninety-fifth series are shown in Figure 95. The results of the ninety-sixth series are shown in Figure 96. The results of the ninety-seventh series are shown in Figure 97. The results of the ninety-eighth series are shown in Figure 98. The results of the ninety-ninth series are shown in Figure 99. The results of the hundredth series are shown in Figure 100.

E

Figs. 28 through 32 are the pictures of the boundary layer, selected to show variations in pressure ratio from below critical to one.

It should be noted that no attempts have been made to obtain quantitative results because such results, using a double pass Schlieren optical system, are extremely difficult to obtain.

The disturbance which may be noted on one side of the nozzle throat of all pictures was caused by a small nick in the corner of the nozzle half. This nick was about .01 inches deep by .01 inches across and about one-eighth of an inch long.

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below which is 10.

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below which is 10.

DISCUSSION OF RESULTS.

As can be seen in Fig. 6, the change from supersonic flow in the throat to subsonic flow downstream of the throat occurred through a multiple shock. Taking Fig. 10 as an example, and considering the occurrences in the direction of flow: the velocity increases through the throat section. Just behind the throat, a region of compression occurs which is thicker in the center of the flow area and decreases to a point before reaching the nozzle boundary, thus indicating the presence of a boundary layer. The downstream side of this region is flat. Next downstream is a region of expansion which appears to be a mirror image of the compression region. At the centerline, the expansion region grades into another compression. Away from the centerline and between the first expansion and the following compression, lies a wedge shaped constant flow region. Following the second compression the above described phenomena appear cyclically.

It appears that other photographs contain the same type of compression-expansion waves though not so symmetrically arranged, and the outer ends of the upstream side of the compressions are seldom so clearly bent downstream from the centerline of the nozzle.

Figs. 14 through 18 show the dissipation of these shocks. They move into the throat and weaken in intensity. They were never observed upstream of the throat section.

DESCRIPTION OF RESULTS

As can be seen in Fig. 2, the diagram shows approximately
flow in the lower to moderate flow conditions of the lower
portion through a multiple state. Being Fig. 2, it is an
example, and illustrating the conditions in the direction of
flow. The velocity increases through the throat section.
This being the throat, a region of expansion occurs which
is visible in the center of the flow area and decreases to a
point before reaching the nozzle boundary, thus indicating
the presence of a boundary layer. The downstream side of
this region is flat. Most downstream is a region of expansion
also which appears to be a limit limit of the expansion
region. At the entrance, the expansion region extends into
another expansion. Away from the nozzle and between
the first expansion and the following expansion, there is
a region which contains flow region. Following the second ex-
pansion the flow is disturbed throughout the entire region.
It appears that other conditions contain the same type
of expansion-expansion waves though not so symmetrically
arranged, and the outer edge of the expansion side of the
expansion is also an edge of the boundary from the
entrance of the nozzle.

Fig. 3 shows the flow in the direction of flow
which. They have been the same and appear to be identical.
They have been the same of the lower section.

This would indicate that the subsonic stream will not support this type of shock over any considerable distance, if at all.

Since other shocks have been observed in a subsonic stream, as was mentioned in the Introduction, the question of the mechanism of the shocks observed becomes paramount. Two attacks are possible; one is to start with the hypothesis that the compression shock forms itself in midstream. Then by observing closely Figs. 28 through 32, which are photographs of the boundary layer, slight waves in the boundary layer can be detected. The key to the nature of the shocks lies in the relation of these waves to the shocks. Considering the boundary layer as a region of constant pressure, the reflection of the compression shock is a "Prandtl-Meyer expansion wedge". As has been noted, an expansion exists after the compression shock. Then the next compression-expansion series follows since supersonic flow may exist out of the first expansion. This process is repeated until finally subsonic flow is attained from the last expansion wedge. There is no apparent relation between one shock (compression and expansion) and the cycle following it.

The weakness in this explanation lies in the hypothesized compression shocks which must start in midstream.

If, on the other hand, consideration is first taken of the boundary layer, which is evidently rather thick, then the following explanation may be made. Slight variations in

the thickness of the boundary layer caused by local oscillations in velocity and pressure such as have been found on investigating the boundary layer of a flat plate (Ref. 3) lead to the conclusion that a convex boundary layer surface may exist. If it is further assumed that the flow in the stream attempts to follow these fluctuations in the boundary layer thickness, then the situation as described in Ref. 4 exists. That is, the flow along a curved boundary is continuous as long as the radii vectors drawn at Machs angles from any point on the boundary do not intersect. When the boundary reaches a sufficient degree of concavity, the radii vectors do intersect and a region of discontinuous flow results. The compression wave thus formed would occur slightly downstream of the concavity in the boundary layer which caused it, thus causing a region of higher pressure at a point where the tendency of the boundary layer is to expand. To equalize the pressure, the boundary layer contracts causing an expansion of the free stream greater than the nozzle walls indicate. The turning of the free stream causes a further depression of the boundary layer which is attempting to expand with the decreasing pressure gradient. As the stream is deflected from the boundary layer a concavity in the boundary layer occurs causing the following compression shock and another cycle of the above mechanism, and so on until subsonic flow results.

In either explanation posed above, each of the multiple shocks would be oblique, not a plane compression shock, and the exit velocity of the stream may be either supersonic or subsonic. In the first explanation posed above, a shock similar to the "hypothesized" shock has been observed in Schlieren pictures of flow around an airfoil taken at the Guggenheim Laboratory at California Institute of Technology. This shock generally slants upstream from the boundary layer and does not lie along a straight line. In the second explanation above, assuming the mean surface of the boundary layer is parallel to the nozzle walls, the shock must slant downstream from the boundary layer, though not necessarily along a straight line. However, if the mean surface of the boundary layer diverges enough from the nozzle walls, then the shock might well slant upstream from the boundary layer. The results of this investigation show no conclusive evidence that the shocks bend in either direction. Also, there is no accurate correlation between any one shock and the boundary layer adjoining it. Hence, no definite conclusion can be reached as to the relation between the waves in the boundary layer and the multiple shocks, except that they both exist at the condition of maximum flow through the nozzle.

The dissipation of these shocks, as may be observed in Figs. 14 through 18, occurs as a weakening of the com-

[illegible]

The situation of these schools, as far as the situation

pression region and a movement upstream into the throat of the nozzle. Apparently the cause of the shocks must move upstream and its intensity must decrease. Since the velocity of the free stream decreases, any cause of the shocks lying in the free stream might be expected to move upstream, but once this motion has started, it would be expected that the motion of the cause of the shocks would not stop at the throat or any other particular point.

On the other hand, if the position of the cause of the shocks is a function of the ratio of the mean boundary layer velocity to the mean free stream velocity, the shocks could conceivably move to a point where this function is again satisfied.

With supersonic flow it is difficult to visualize how a shock caused by free stream disturbances can do anything but move downstream at a velocity equal to the difference between the local sonic velocity and the velocity of the free stream. Figs. 6 through 13 show, however, that a compression wave may be traced from one figure to the next and that the motion of individual shocks may be traced going downstream, then reversing and moving upstream. The rate of change of this motion is about two hundred cycles per second. The region of this oscillation is from the downstream side of the throat section to about one throat diameter downstream of this point.

position (which was a constant distance from the origin
of the system). Apparently the source of the waves must
have approached and the intensity had increased. Since the
velocity of the wave is constant, any change of the
distance from the origin must be due to the motion of the
source, and when this motion is stopped, it would be ex-
pected that the motion of the source would not
stop at the instant of any other position point.

On the other hand, if the position of the source of the
motion is a function of the ratio of the wave velocity to
velocity of the wave (which is unity), the source would
consequently move to a point where this function is unity
relative.

With reference to the ratio of the wave velocity to
velocity of the wave (which is unity), the source would
consequently move to a point where this function is unity
relative. The ratio of the wave velocity to velocity of the
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the wave velocity to velocity of the wave (which is unity).

It is rather easy to visualize this condition when the upstream variation in the thickness of the boundary has a motion of the same frequency. As described in Ref. 4, this oscillation of boundary layer velocity and pressure actually exists on a flat plate in a subsonic stream and hence may be supposed to occur on the surface of the nozzle in a supersonic stream.

It was noted that when the shock was not too far downstream of the throat, but was in existence, a swishing sound could be heard issuing from the nozzle. As the back pressure was decreased and the shock moved further downstream, the sound decreased in frequency and intensity until it could not be heard.

It was further noted that with the maximum pressure difference obtainable across the nozzle the nature of the shock changed slowly with time. When the full pressure drop was attained by opening the valves controlling the flow through the nozzle, the shock appearing on the screen appeared similar to that shown in Figs. 26 and 27. After about forty-five seconds to a minute, this shock would have disappeared and in its place could be seen the multiple shocks similar to Fig. 8 and usually well downstream of the throat. The nature of this slow change was not observed. If the flow was instantaneously interrupted, the single shock of Fig. 27 would again appear.

It is rather easy to identify this condition when the upstream variation in the thickness of the boundary and a motion of the same thickness. As described in Fig. 4, this condition of boundary layer velocity and pressure actually exists on a flat plate in a turbulent stream and hence may be imagined to occur on the surface of the particle is a turbulent stream.

It was noted that when the above was not the case, the thickness of the layer, but was in evidence, a rotating body could be kept from the surface. As the body rotated was increased and the speed of rotation was increased, the speed decreased in thickness and finally all it could be held.

It was further noted that with the maximum pressure difference possible across the particle the motion of the body changed slowly with time. When the full pressure drop was applied to operate the valve controlling the flow through the nozzle, the flow stopped on the surface of the particle in that case in Fig. 4. After about forty-five seconds to a minute, this flow would have disappeared and in the case of the valve the flow would return to the initial state and usually well downstream of the body. The nature of this flow change was not constant. If the flow was instantaneously interrupted, the change of the flow would be rapid.

Professor Keenan has suggested that this may be a temperature effect. The stream being cooler than the surroundings would in time cool the walls of the nozzle and the stream itself would increase in velocity due to the heat absorbed by the stream. As the walls of the nozzle cooled, less heat would be transmitted to the stream, thus decreasing the velocity, and hence the strength of the shock, permitting the multiple shocks to form.

As can be clearly seen in Figs. 25, 26 and 27, a condensation shock was observed. This shock was annoying in that it blanked out some pictures that might otherwise have been of interest. However, its position in relation to the throat remained fairly constant and was generally downstream of the multiple oblique shocks when the pressure ratio across the nozzle was near critical. It is mentioned by way of explanation of the darkened region towards the nozzle exit. It is not felt that this condensation shock had any marked effects on the results. A more complete discussion of condensation shocks may be found in Ref. 7.

The results presented are far from conclusive as to the manner of dissipation of the shocks, as to the nature of the shocks themselves, and as to the relation between the boundary layer and the shocks. It would have been interesting, had time permitted, to find the relation between the boundary layer and the shocks. This could have been

Profoundly deeply we are indebted to the
Department of the Interior for the report
which is now before us. It is a most
valuable contribution to the knowledge
of the subject, and we are sure that
it will be of great service to the
Government in its efforts to
bring about a more complete
conservation of the public lands.
The report is a most valuable
contribution to the knowledge
of the subject, and we are sure
that it will be of great service
to the Government in its efforts
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contribution to the knowledge
of the subject, and we are sure
that it will be of great service
to the Government in its efforts
to bring about a more complete
conservation of the public lands.

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done by taking a run similar to those made with an angle of forty-five degrees between the nozzle axis and the Schlieren knife edge. Correlation of such a set of pictures with those obtained could have been much more informative than the results obtained.

CONCLUSIONS.

1. The oblique shock observed in this investigation dissipates very quickly or never exists in a subsonic stream.

2. The results indicate that there is a close correlation between the boundary layer and the oblique shocks existing.

3. The noise issuing from the mouth of the nozzle, at pressure ratios slightly below critical, is caused by oscillation of the shock in "steady state".

4. The condensation shock presents no problem in this type of investigation since it occurs downstream of the effects observed.

5. Two distinct types of dynamic change occur under the conditions investigated; namely, a high speed oscillation of the multiple shocks, and a relatively slow change from a plane compression shock to the multiple shocks. Both effects occur with no change in the pressure ratio across the nozzle.

1. The following items are listed in this investigation:

5. The Federal Reserve Bank is a single entity.

3. The volume bearing from the mouth of the mouth,

4. The investigation also provides an example of the type of investigation that is being conducted.

Two distinct types of chemical change were noted in the conditions investigated: a slow, steady change in the weight of the material and a relatively slow change in the weight of the material.

There is a large number of people in the world who are not interested in the world's affairs.

RECOMMENDATIONS.

A quantitative Schlieren investigation of the relation between the boundary layer and the shocks in a supersonic stream might lend much light on the formation and dissipation shocks.

CONCLUSIONS

A comparative analysis of the relationship between the boundary layer and the shock in a supersonic stream shows that the formation of a shock wave is not dissipationless.

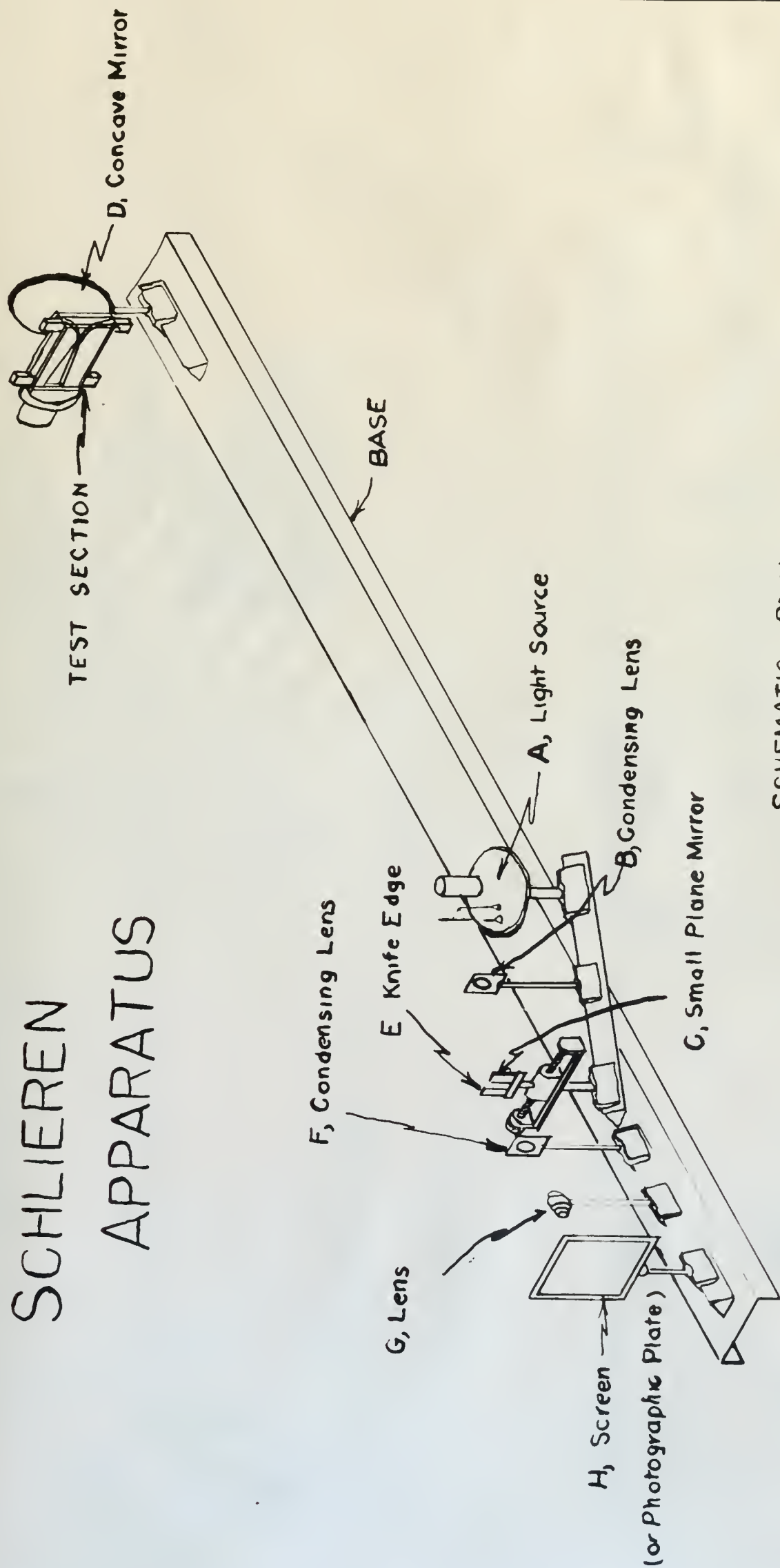
The results of the calculations show that the shock wave is a dissipative process and that the entropy increases across the shock.

The calculations also show that the shock wave is a discontinuity in the flow field and that the flow properties change abruptly across the shock.

The results of the calculations show that the shock wave is a dissipative process and that the entropy increases across the shock.

The calculations also show that the shock wave is a discontinuity in the flow field and that the flow properties change abruptly across the shock.

SCHLIEREN APPARATUS



SCHEMATIC PLAN

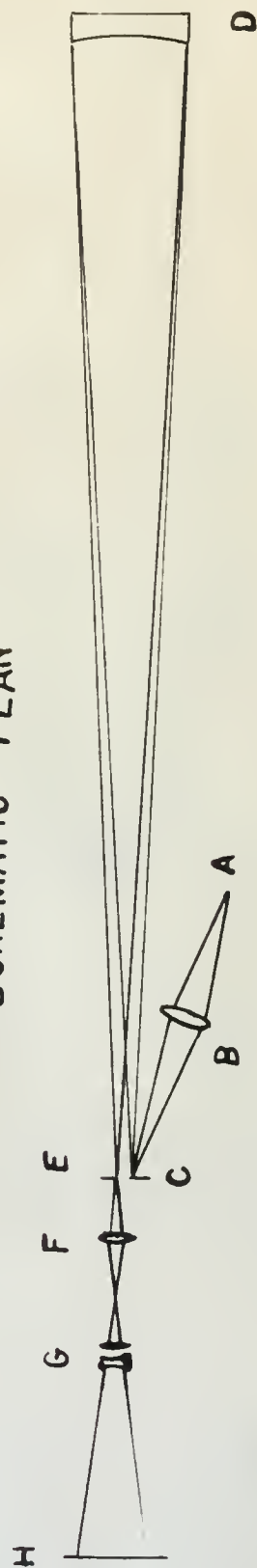


Fig. 1

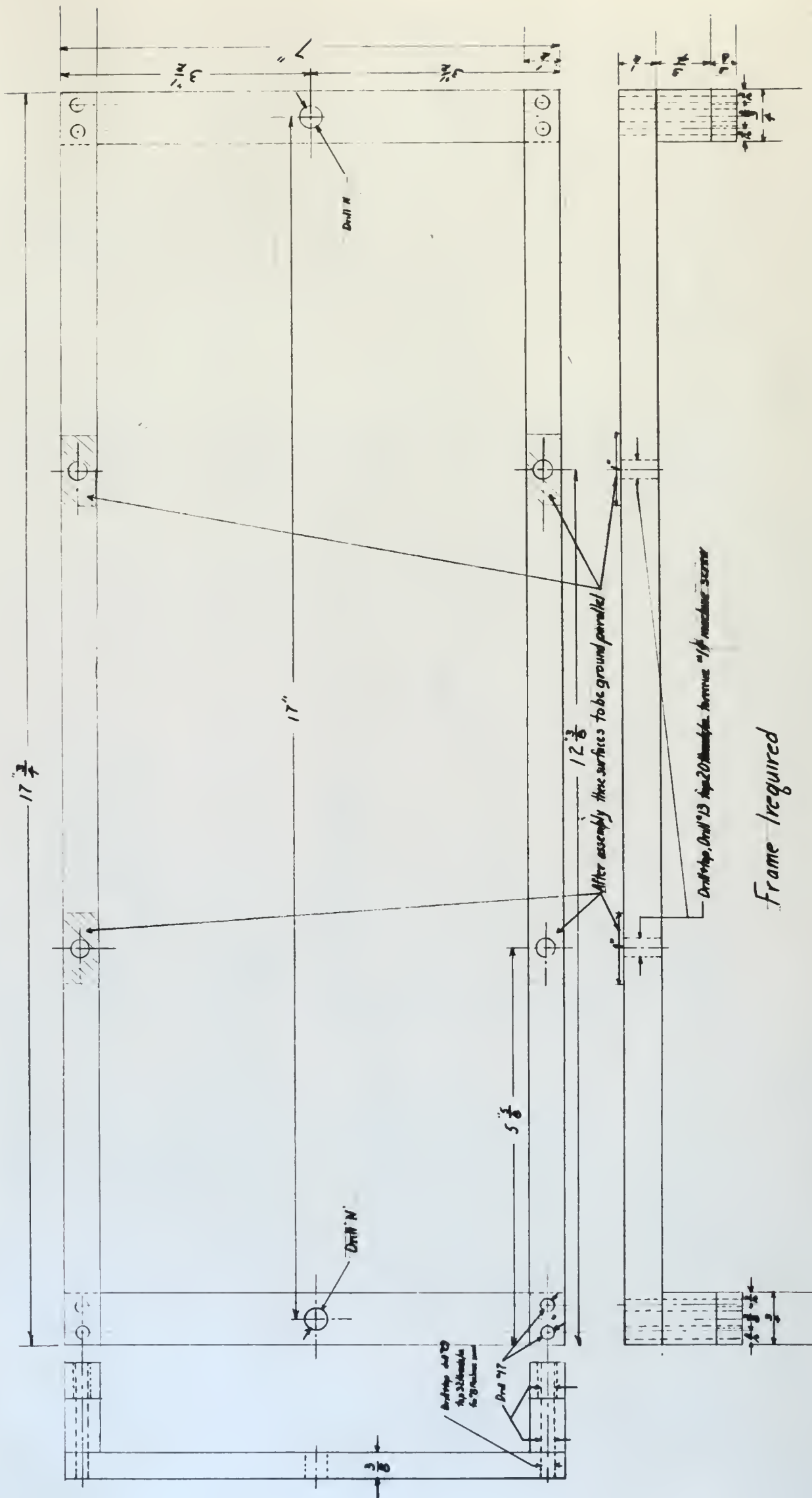


Fig. 3

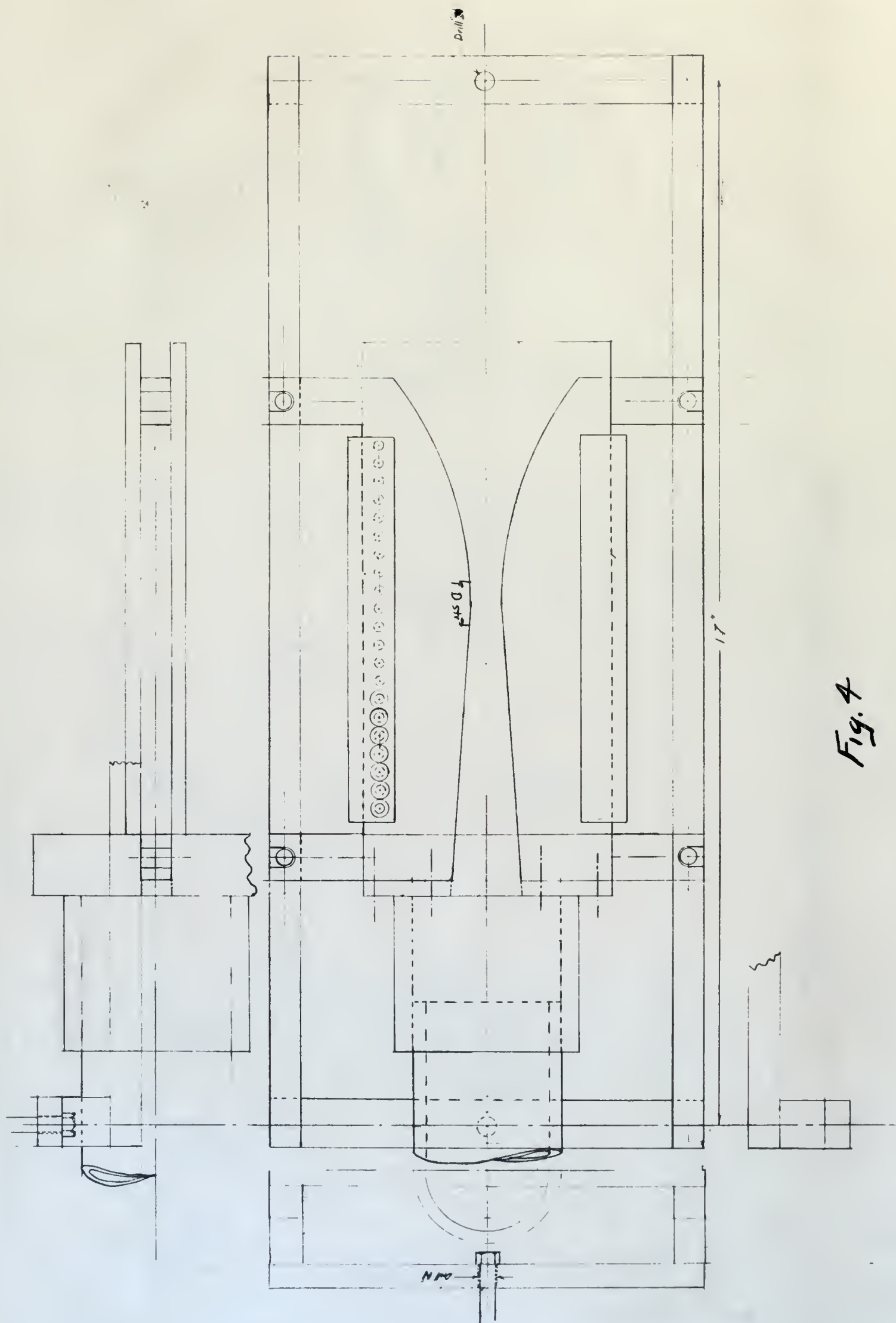
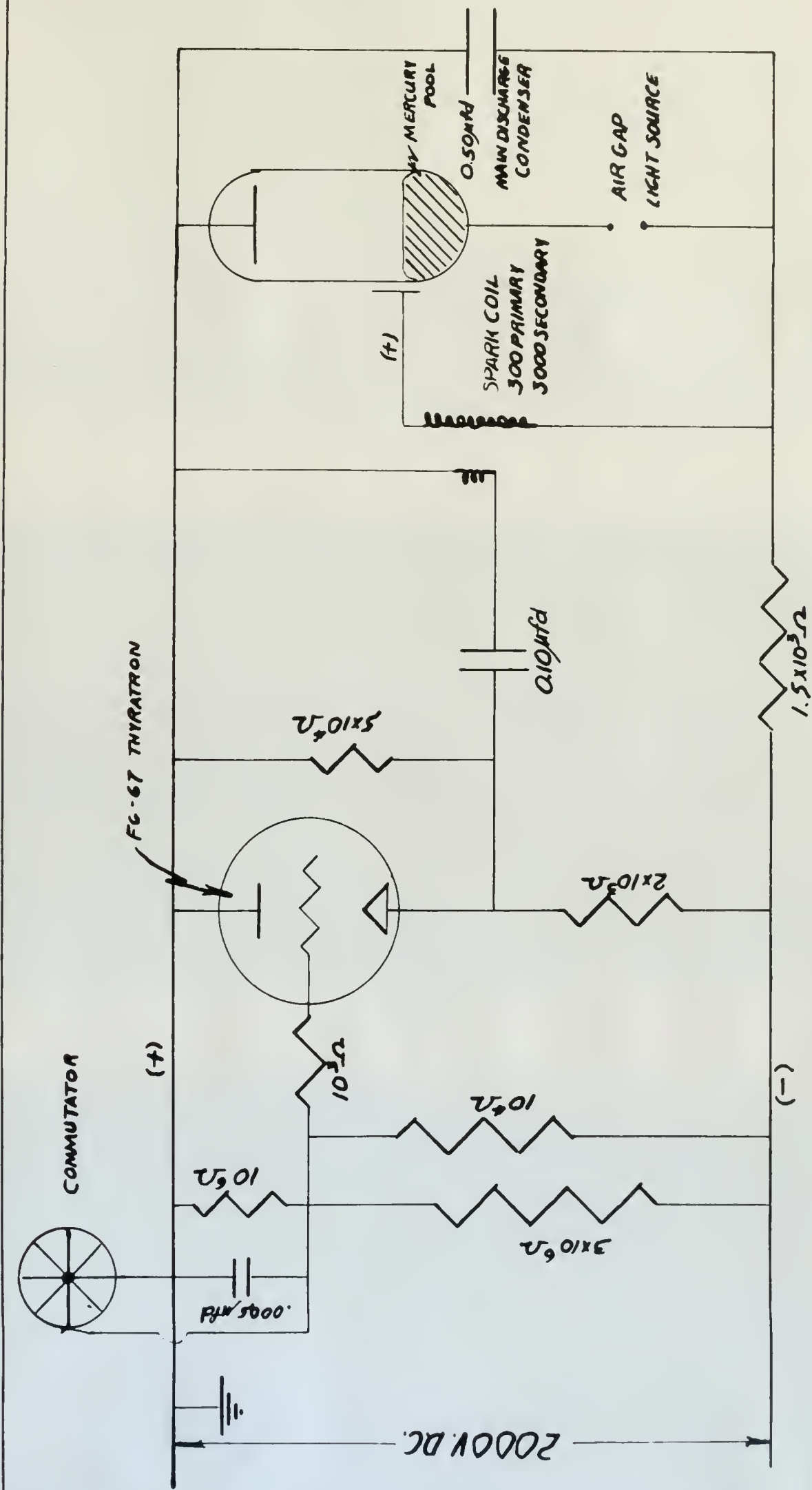


Fig. 4



Schematic Wiring Diagram of Light Source

Fig. 5

FIGS. 6 to 14.

SERIES 1.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, CONSTANT
ENTRANCE PRESSURE, ATMOSPHERIC
TIME INTERVAL BETWEEN PICTURES, ONE FIVE HUNDREDTH SECONDS
EXPOSURE TIME, FIVE MICROSECONDS

FIG. 6 to 14.

SHINE I.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, MOISTURE RATIO TO SATURATION, CONSTANT
SATURATION PRESSURE, TEMPERATURE
TIME INTERVAL BETWEEN VIBRATIONS, ONE FIVE HUNDREDTHS SECONDS
KILOPASCAL TIME, FIVE HUNDREDTHS



FIG. 6.

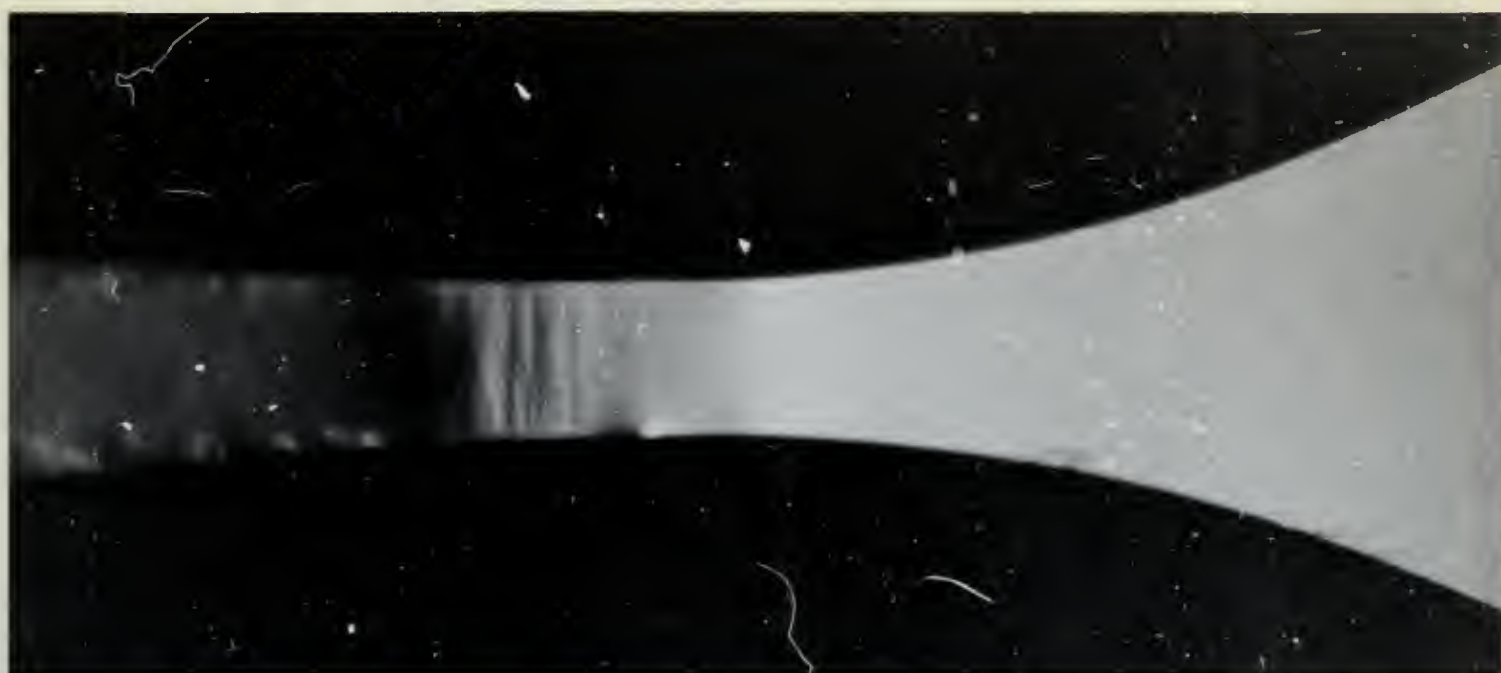


FIG. 7.



FIG. 8.



FIG. 9.



FIG. 10.

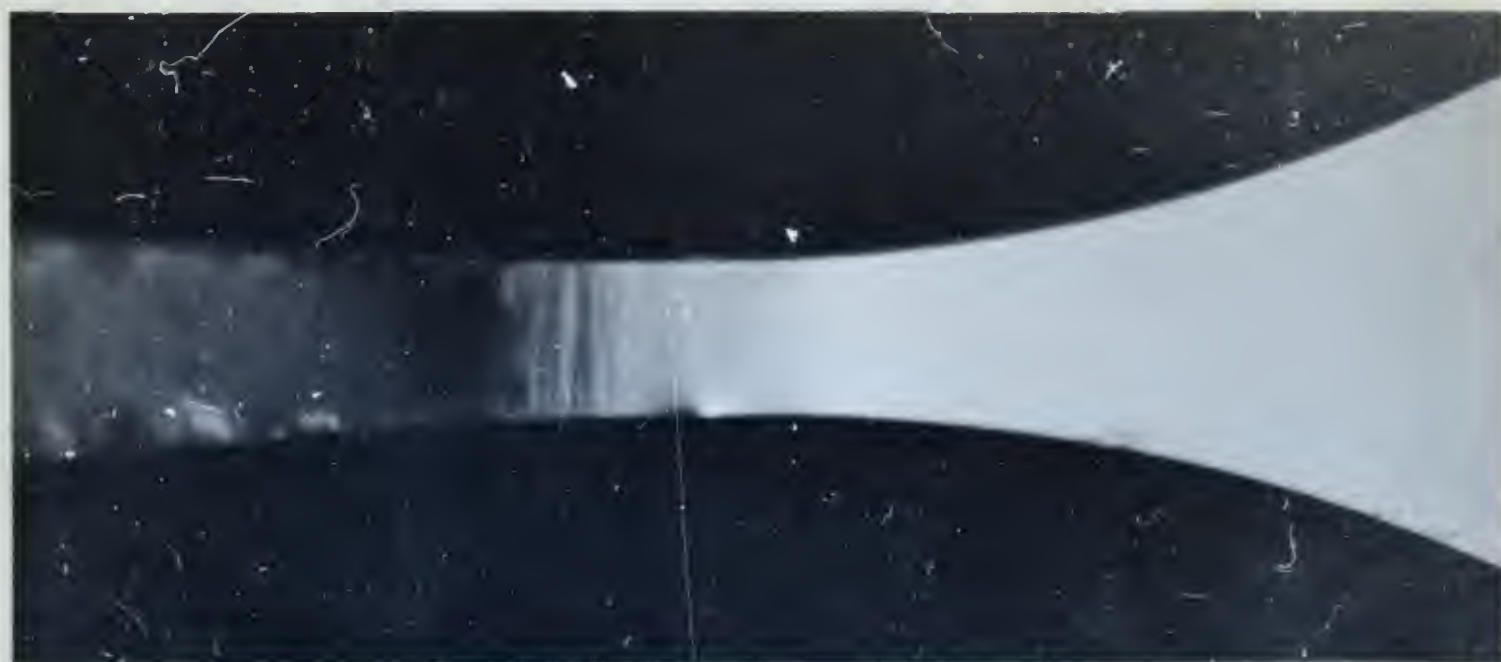


FIG. 11.



FIG. 12.



FIG. 13.

FIGS. 14 to 19.

SERIES 2.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, INCREASING
ENTRANCE PRESSURE, ATMOSPHERIC
TIME INTERVAL BETWEEN PICTURES, ONE FIVE HUNDREDTH SECONDS
EXPOSURE TIME, FIVE MICROSECONDS

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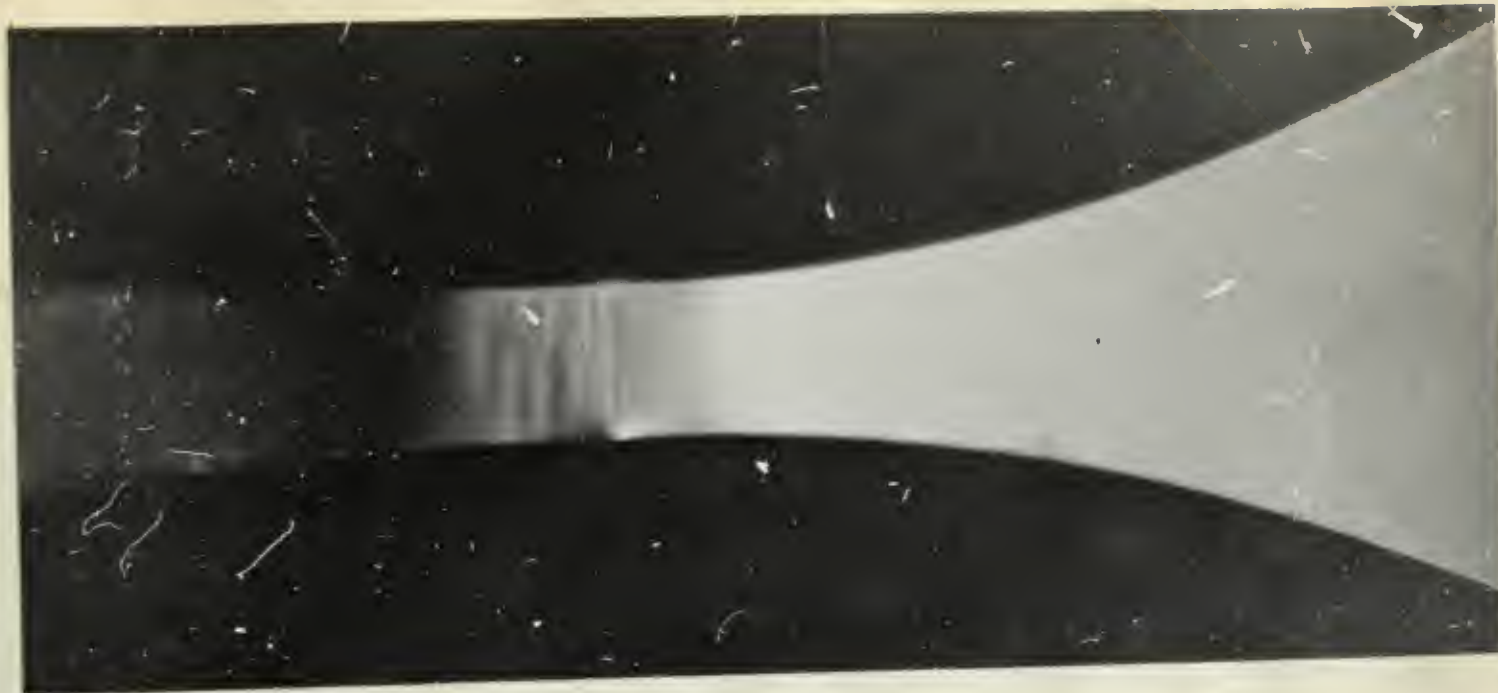


FIG. 14.



FIG. 15.



FIG. 16.



FIG. 17.



FIG. 18.



FIG. 19.

FIGS. 19 to 28.

SERIES 3.

TAKEN MAY 9, 1946, AT 3 P.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, DECREASING
ENTRANCE PRESSURE, ATMOSPHERIC
TIME INTERVAL BETWEEN PICTURES, ONE FIVE HUNDREDTH SECONDS
EXPOSURE TIME, FIVE MICROSECONDS

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WINE 3.

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FIG. 20.



FIG. 21.



FIG. 22.



FIG. 23.



FIG. 24.



FIG. 25.

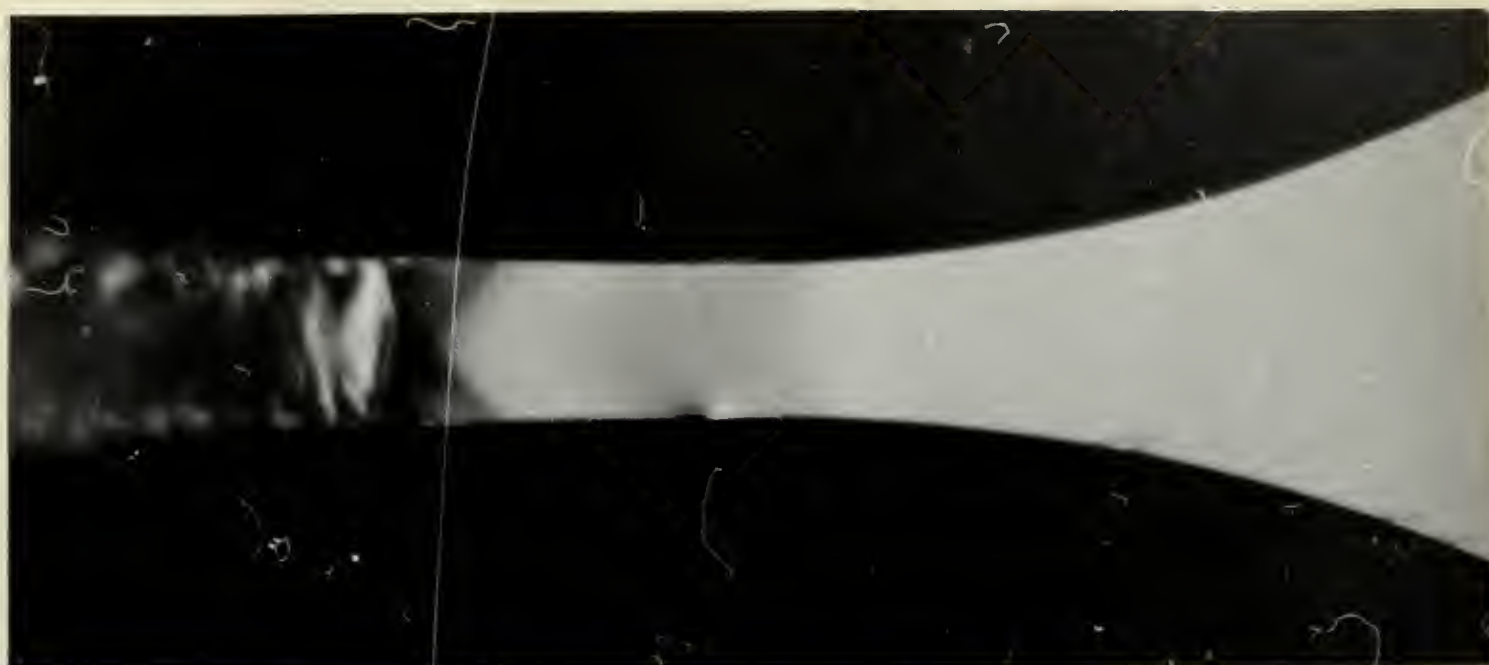


FIG. 26.



FIG. 27.

FIGS. 28 THROUGH 32.

TAKEN MAY 12, 1946, AT 10 A.M., AT M.I.T.
PRESSURE RATIO, NOZZLE EXIT TO ENTRANCE, INCREASING
ENTRANCE PRESSURE, ATMOSPHERIC
EXPOSURE TIME, FIVE MICROSECONDS

Note: Pictures are not separated by constant time
interval but are selected to show typical
structures found.



FIG. 28.



FIG. 29.



FIG. 30.



FIG. 31.



FIG. 32

APPENDIX I.

DETAILED DESCRIPTION AND DISCUSSION OF APPARATUS.

THE SCHLIEREN EQUIPMENT

The Schlieren optical method was used to observe the phenomena investigated. The system used is sketched in Fig. 1. It consists essentially of a light source, a small plane mirror, a spherical concave mirror with a twenty-four foot focal length, a knife edge, a screen of ground glass, or photographic film, a system of corrected convex lenses, and the model to be observed.

Referring to Fig. 1, light is collected from the source "A", by the condensing lens "B", and focused on the small plane mirror "C". The point of focus is a point on the side of the plane mirror nearest the optical axis of the bench. A portion of the image of the source is allowed to pass between the mirror and the optical axis. This insures a sharp edge on the image cast back to the knife edge and permits accurate sensitivity adjustments. The light from the plane mirror is then cast through the test section on to the concave mirror "D". Thence the light is reflected back through the test section to the knife edge "E".

The knife edge is in the same plane as the plane mirror. This plane is located at one half the focal length of the mirror away from it, as measured along the optical axis. The

RELATIVE HUMIDITY AND LIQUIDITY OF AIR

THE RELATIVE HUMIDITY

The following optical method was used to observe the
 phenomena investigated. The system used is sketched in
 Fig. 1. It consists essentially of a light source, a small
 plane mirror, a spherical convex mirror with a twenty-four
 inch focal length, a knife edge, a system of ground glass,
 or phase-contrast film, a system of horizontal ground glass,
 and the model to be observed.

Referring to Fig. 1, light is collected from the source
 "A", by the condensing lens "B", and focused on the small
 plane mirror "C". The point of focus is a point on the side
 of the plane mirror nearest the optical axis of the model.

A position of the lamp of the source is allowed to pass
 between the mirror and the optical axis. This causes a
 sharp edge on the lamp cast back to the knife edge and pre-
 sents accurate sensitivity adjustment. The light from the
 plane mirror is then cast through the lens section on to the
 convex mirror "D". Thence the light is reflected back
 through the lens section to the knife edge "E".

The knife edge is in the same plane as the plane mirror.
 This plane is located at one half the focal length of the
 mirror away from it, as measured along the optical axis. The

knife edge is parallel to the edge of the mirror nearest the optical axis, so that light passing the knife edge appears as a sharply defined rectangular slit. The condensing lens "F" collects the light and the lens "G" focuses the light so that the test section is defined on the screen.

A decreasing density gradient toward the knife-edge side of the test section (downstream) causes a deflection of the rays passing through the test section away from the knife edge. An increasing pressure gradient in this direction refracts the light toward the knife edge. Thus, a decreasing density gradient in the direction of flow appears as a lighter region and an increasing one appears as a dark region.

A rotating table was used to mount the light source, so that the apparatus would be lined up and adjusted with a steady source; then pictures could be taken with the flash source by merely rotating the table.

The sensitivity is adjusted by moving the knife edge into or out of the beam of light reflected by the concave mirror, by means of a micrometer screw. Moving the knife edge into the beam increases the sensitivity. That is, smaller refractions of the light are blacked out on the viewing screen by the knife edge.

A complete discussion of the adjustments to the apparatus may be found in references (1) or (2).

knife edge is parallel to the edge of the mirror surface
the optical axis, so that light passing the knife edge ap-
pears as a sharply defined rectangular slit. The constant
light intensity collected the light and the light intensity
the light so that the light intensity is defined on the screen.
A rectangular domain is defined across the knife-edge
side of the light section (downstream) across a reflection
of the light passing through the knife edge. The light
knife edge. An interesting phenomenon is observed in this direc-
tion towards the light towards the knife edge. When a
decreasing intensity gradient in the direction of the screen
as a linear region and an increasing one appears as a light
region.

A rotating table was used to mount the light source,
so that the experiment would be done up and rotated with a
steady source; then distance could be taken with the plane
source by merely rotating the table.

The sensitivity is adjusted by rotating the knife edge
into or out of the beam of light reflected by the rotating
mirror, by means of a micrometer screw. Moving the knife
edge into the beam increases the sensitivity. When it is
similar variations of the light are observed on the screen
ing towards the knife edge.

A complete discussion of the adjustments to the apparatus
may be found in references (1) or (2).

THE GLASS NOZZLE WALLS

The glass used on the sides of the nozzle had a large effect on the results obtained. First tried, was selected plate glass. This glass was high quality plate glass selected by means of an interferometer for flatness and parallelism of the planes. Selected points in each piece used were examined and at no place was a curvature of greater than thirty seconds of arc observed. However, when placed on the test section and observed through the apparatus, the effects of the glass were smaller but of the same order of magnitude as the compression shock which was under investigation. See Fig. A, Appendix I. Therefore, it was necessary to obtain two optically flat pieces of glass from which no glass effects could be observed through this apparatus. See Fig. 18.

Clamping stresses were avoided by holding the glass in place with cellulose tape. Pressure stresses were small because pressure differences were small, of the order of seven pounds per square inch, and the areas affected were small. The thickness of the glass used to obtain the final results totaled one inch, that is, each piece was one-half inch thick.

THE HIGH SPEED MOVIE CAMERA

To obtain a series of pictures with a short time interval between pictures, a thirty-five millimeter, high speed

THE GLASS MOUNTING

The glass case or the block of the material has a large effect on the results obtained. First trial, was selected glass plate. This glass was very highly polished and tested by means of an interferometer for flatness and

parallelism of the plates. Coloured points in each glass used were examined and at no place was a variation of colour seen thirty seconds of the observation. However, when placed on the test section and observed through the eyepiece, the effects of the glass were smaller than at the same order of magnification as the comparison made with the water immersion. See fig. 4, Appendix I. Therefore, it was necessary to obtain the optical flat plates of glass from which no glass effects could be observed through this ap-

erture. See fig. 14.

Optical surfaces were avoided by holding the glass in place with oil-soluble tape. The same procedure was used for sections prepared with small, at the same of never found per square inch, and the glass affected was small. The thickness of the glass used to obtain the final results varied one inch, two is, and three are one-half inch thick.

THE MOUNTING MEDIA

To obtain a series of sections with a small time lag for between plates, a thirty-five millimeter, six glass

camera was used. The camera consisted of two reels, one for unexposed film, and the other for winding the exposed film, and a sprocket guide wheel, all encased in a light tight box fitted with an exposure aperture. A motor drove the exposed film reel, and the sprocket wheel, turned by tension in the film from the exposed film reel, turned a commutator which actuated the light source. Frames were separated by the flashing light source. The camera and light source were capable of taking pictures at any rate of speed up to twelve hundred frames per second, the speed being controlled by a governor on the driving motor. Timing of the speed was effected by a sixty cycles per second spark at the edge of the film, leaving a blackened area on the edge of the film for each sixtieth of a second of time elapsed.

LIGHT SOURCES

The steady light source consisted of a filament electric lamp.

Several types of flashing sources were used. For the trial single pictures an "Edgerton Flash Tube" was used. This consists of a spark gap in an inert gas. The spark is corded, that is, it is made to pass through a glass tube of about one eighth inch inside diameter. The spark was about one and one-half inches long. (Ref. (2)).

For the high speed series of pictures the same type of tube was tried and found unsuccessful because the spark was

not corded into a narrow enough region. This motion of the spark caused the light to the plane mirror at times to be all on the mirror so that no definition of the edge of the mirror could be detected at the knife edge, hence losing control of the sensitivity adjustment, and at times to be completely off the plane mirror so that no light passed through the remainder of the system.

In an effort to reduce the wandering of the spark an air spark gap was tried, with no attempt made to cord the spark, but wandering of the spark materially reduced by reducing the length of the air gap to about one-quarter of an inch. This scheme was satisfactory but not excellent, since some variation in the density of the frames could be observed.

The mechanism for producing the spark is sketched diagrammatically in Fig. 5. An impulse from the commutator permitted the thyatron to pass current which in turn allowed the 0.10 microfarad condenser to discharge. This caused current to commence flowing in the primary of the spark coil which induced a voltage in the secondary. This voltage in the secondary was enough to "fire" the mercury tube and cause a breakdown across the air gap. Once the mercury tube commenced to pass electrons, the main discharge condenser, discharged across the air gap and through the mercury tube. The 1500 ohm resistor prevented firing of

not covered under a patent issued to the inventor. This device by the spark causes the light to the glass mirror at times to be all on the mirror as there is reflection of the light of the mirror could be detected at the light wave, hence, being control of the sensitivity adjustment, and as time to be completely off the glass mirror to shut no light passed through the remainder of the system.

In an effort to reduce the amount of the spark as air space was used, with an attempt made to point the spark, but reduction of the spark actually reduced by reducing the length of the air gap to about one-quarter of an inch. This system was satisfactory but not excellent, since some variation in the density of the spark could be observed.

The mechanism for producing the spark is described electrically in Fig. 3. It isolates from the commutator generated the spark in such a way as to form a low 5.10 microsecond commutator in discharge. This caused current to pass through the primary of the spark coil which caused a voltage in the secondary. This voltage in the secondary was enough to "fire" the primary tube and cause a breakdown across the air gap. Once the primary tube commutator is gone, the spark, and the main discharge mechanism, is gone. The spark is produced by the primary tube. The 5.10 microsecond commutator is the spark.

the air gap once the main discharge condenser had discharged, but permitted this condenser to build up in voltage when no current was flowing through the air gap circuit. The rectifying nature of the mercury tube prevented a secondary spark from forming due to any inductance that probably existed in the actual main discharge circuit.

PHOTOGRAPHIC TECHNIQUE

It was found that the efficiency of the spark was materially reduced as to its effect on photographic plate when the spark was allowed to discharge through air rather than through an inert gas. Hence, in order to keep the exposure time short, it was found necessary to use the fastest obtainable movie film. It was not considered expedient to hypersensitize slower film due to the uncertainties involved, and the possible striations in the photographic film speed. The film used was Eastman Kodak Company's "Super XX".

In the development of the film it was found that maximum contrast could be obtained by chemically fogging the film very slightly. This merely ensured full development of all light struck portions of the exposed film. In order to do this the commercial developer "D-11" produced by Eastman Kodak Company was used and a developing time of sixteen minutes was used. The temperature of the developer was maintained as nearly at 68 degrees F. as possible to prevent excessive grain size in the negative.

the air got once the main discharge stream had been
stopped, but continued this movement to build up in
volume when no current was flowing through the air gap
between the two electrodes. The resulting nature of the current was pre-
sented a secondary effect from the fact that the air
was not uniformly mixed in the space and the discharge
stream.

DISCHARGE CHARACTERISTICS

It was found that the discharge at the start was
relatively uniform as to the extent of the discharge plane
when the spark was allowed to discharge through the system
that formed in the air gap. However, in order to keep the dis-
charge from being too large, it was found necessary to use the largest
possible spark gap. It was not considered expedient to
operationalize along this line and in the experimental method
and the possible variations in the discharge film speed.
The film used was Eastman Kodak Company's "Kodak X".
In the experiment of this film it was found that the
most accurate results were obtained by operating the
film very slowly. This means that the film was exposed
at all times under control of the exposure film. In order
to do this the camera was equipped with a "Kodak X" camera
which was used and a developing film of sixteen in-
ches was used. The exposure of the film was maintained
as nearly as possible to the present exposure
rate also in the future.

HEAT STRIATIONS

Heated wires were placed across the nozzle entrance parallel to the optical axis, in an effort to follow streamlines in the flow through the nozzle. However, these were found to disrupt the flow considerably and at maximum flow it was not feasible to heat the wires enough to follow the streamlines through the throat. It was feared that too much heat applied locally near the glass walls of the nozzle might break them. In obtaining the final results this scheme was abandoned.

ADJUSTMENTS AFFECTING RESULTS

It was found that relatively small movements of the light source in a lateral direction caused shifts in the image which varied the sensitivity from "dark field" to no sensitivity at all. Movements of the order of a sixteenth of an inch from the mean were all that were necessary to provide this change in the position of the image relative to the knife edge. It was further found that motion of the light source of the same order of magnitude along the optical axis gave the same effect on the viewing screen due to motion of the focal point of the concave mirror relative to the knife edge.

It was found that when the glass walls of the test section were perpendicular to the optical axis reflections from the surfaces of the glass threw stray light into the screen that was not tolerable. Hence, all pictures are taken with

THEORY OF THE

Heated wires were placed across the middle of the
parallel to the optical axis. In an effort to follow the
lines in the flow through the nozzle. However, these wires
tended to disturb the flow considerably and at various times
it was not possible to pass the wires through the nozzle and
at various times through the throat. It was found that the
most best applied locally near the glass walls of the nozzle
right from the throat. In obtaining the final results this method
was abandoned.

EXPERIMENTAL APPARATUS

It was found that relatively small amounts of the
liquid were in a liquid state and were in the
large and varied the density from that of
to practically all. Experiments at the throat of a nozzle
of an area from the area were all that were necessary to
provide this change in the position of the liquid relative to
the nozzle edge. It was further found that the position of the
liquid surface of the same order of magnitude along the optical
axis gave the same effect on the viewing system and the motion
of the focal point of the camera with respect to the liquid
edge.

It was found that when the liquid was at the throat the
the very position of the liquid was the same as the position of
the surface of the liquid when the light was at the throat
that was not relative. Hence, all distances are taken with

an angle of about four degrees between the optical axis and a perpendicular to the plane of the glass walls of the test section.

The interval between frames was taken at about one five-hundredth of a second because the spark source was more dependable at this slow speed, and because some experimental shots taken at higher speeds up to eleven hundred frames per second indicated that local movements of the shock occurred at much higher speeds. The camera would only handle one hundred foot lengths of film and at higher speeds, after allowing for the camera to steady on the set speed, too short a total time interval was left for the manual operation of the butterfly valve. It was thought that the sudden closure of the valve by automatic means might inject air inertia problems into an already complicated one. Therefore, the high speed series of pictures taken are not continuous; that is, when shown through a moving picture camera they do not show the movement of the multiple shocks relative to each other in a smooth continuous motion.

The negatives of the results have not been cut, so that each run remains intact as it was made. These negatives are presented with the original copy of this thesis to M.I.T.

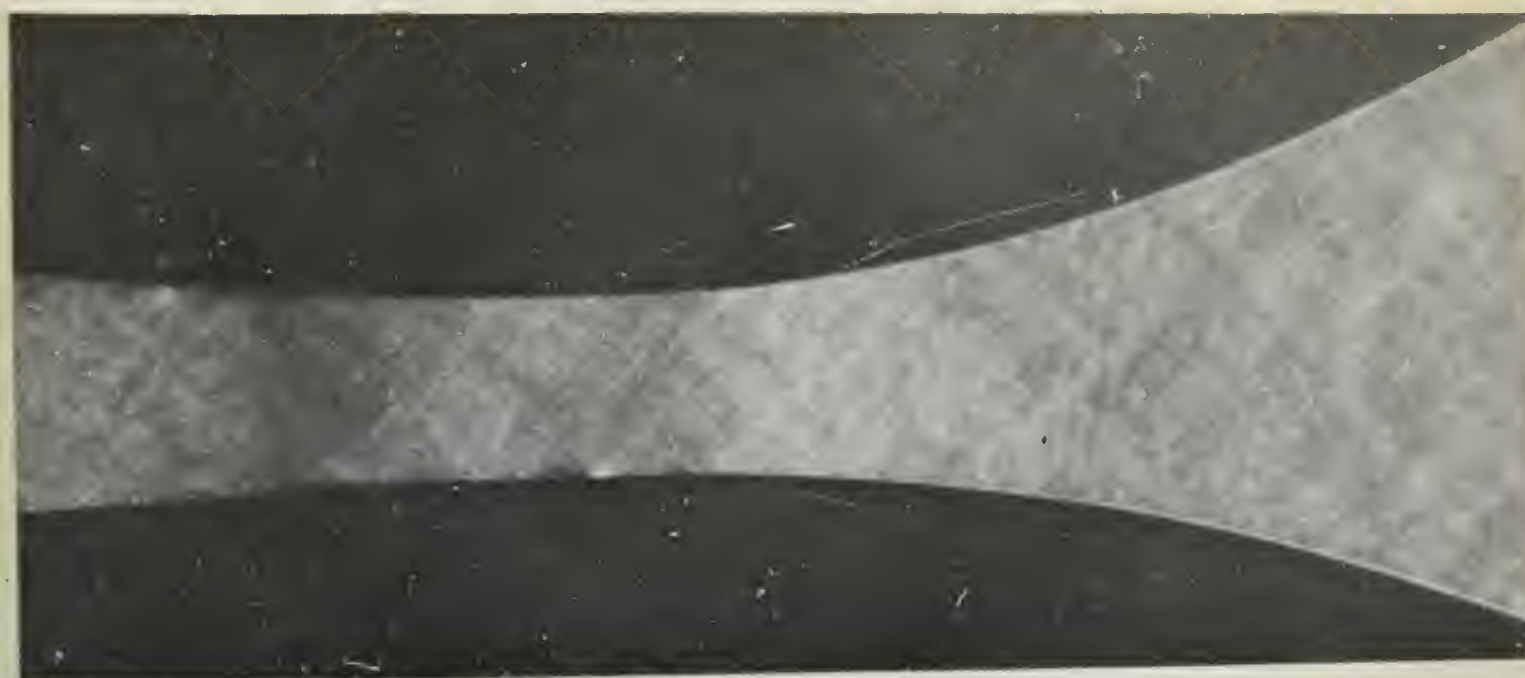


FIG. A.

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